photons is evidence, Einstein claimed, that the photons were endowed with identical properties when emitted, not that they are subject to some bizarre long-distance quantum entanglement.

For close to five decades, the issue of who was right—Einstein or the supporters of quantum mechanics—was left unresolved because, as we shall see, the debate became much like that between Scully and Mulder: any attempt to disprove the proposed strange quantum mechanical connections and leave intact Einstein's more conventional view ran afoul of the claim that the experiments themselves would necessarily contaminate the very features they were trying to study. All this changed in the 1960s. With a stunning insight, the Irish physicist John Bell showed that the issue could be settled experimentally, and by the 1980s it was. The most straightforward reading of the data is that Einstein was wrong and there can be strange, weird, and "spooky" quantum connections between things over here and things over there.[5]

The reasoning behind this conclusion is so subtle that it took physicists more than three decades to appreciate fully. But after covering the essential features of quantum mechanics we will see that the core of the argument reduces to nothing more complex than a Click and Clack puzzler.

Casting a Wave

If you shine a laser pointer on a little piece of black, overexposed 35mm film from which you have scratched away the emulsion in two extremely close and narrow lines, you will see direct evidence that light is a wave. If you've never done this, it's worth a try (you can use many things in place of the film, such as the wire mesh in a fancy coffee plunger). The image you will see when the laser light passes through the slits on the film and hits a screen consists of light and dark bands, as in Figure 4.1, and the explanation for this pattern relies on a basic feature of waves. Water waves are easiest to visualize, so let's first explain the essential point with waves on a large, placid lake, and then apply our understanding to light.

A water wave disturbs the flat surface of a lake by creating regions where the water level is higher than usual and regions where it is lower than usual. The highest part of a wave is called its *peak* and the lowest part is called its *trough.* A typical wave involves a periodic succession: peak followed by trough followed by peak, and so forth. If two waves head toward

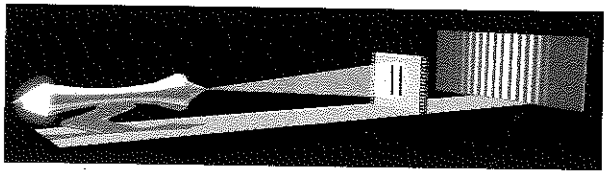
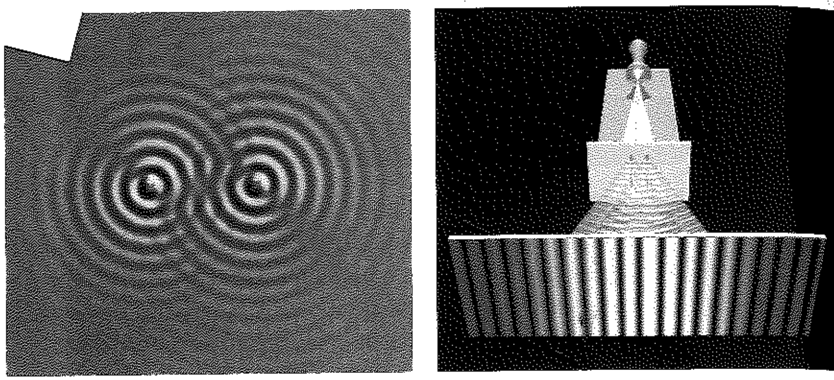


Figure 4.1 Laser light passing through two slits etched on a piece of black film yields an interference pattern on a detector screen, showing that light is a wave.

each other—if, for example, you and I each drop a pebble into the lake at nearby locations, producing outward-moving waves that run into each other—when they cross there results an important effect known as *interference,* illustrated in Figure 4.2a. When a peak of one wave and a peak of the other cross, the height of the water is even greater, being the sum of the two peak heights. Similarly, when a trough of one wave and a trough of the other cross, the depression in the water is even deeper, being the sum of the two depressions. And here is the most important combination: when a peak of one wave crosses the trough of another, they tend to cancel each other out, as the peak tries to make the water go up while the trough tries to drag it down. If the height of one wave's peak equals the depth of the other's trough, there will be perfect cancellation when they cross, so the water at that location will not move at all.

The same principle explains the pattern that light forms when it passes through the two slits in Figure 4.1. Light is an electromagnetic wave; when it passes through the two slits, it splits into two waves that head toward the screen. Like the two water waves just discussed, the two light waves interfere with each other. When they hit various points on the screen, sometimes both waves are at their peaks, making the screen bright; sometimes both waves are at their troughs, also making it bright; but sometimes one wave is at its peak and the other is at its trough and they cancel, making that point on the screen dark. We illustrate this in Figure 4.2b.

When the wave motion is analyzed in mathematical detail, including the cases of partial cancellations between waves at various stages between peaks and troughs, one can show that the bright and dark spots fill out the bands seen in Figure 4.1. The bright and dark bands are therefore a telltale sign that light is a wave, an issue that had been hotly debated ever since Newton claimed that light is not a wave but instead is made up of a

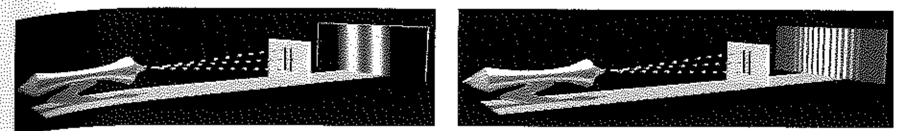


(a) (b)

Figure 4.2 (**a**) Overlapping water waves produce an interference pattern. (**b**) Overlapping light waves produce an interference pattern.

stream of particles (more on this in a moment). Moreover, this analysis applies equally well to *any* kind of wave (light wave, water wave, sound wave, you name it) and thus, interference patterns provide the metaphorical smoking gun: you know you are dealing with a wave if, when it is forced to pass through two slits of the right size (determined by the distance between the wave's peaks and troughs), the resulting intensity pattern looks like that in Figure 4.1 (with bright regions representing high intensity and dark regions being low intensity).

In 1927, Clinton Davisson and Lester Germer fired a beam of electrons—particulate entities without any apparent connection to waves—at a piece of nickel crystal; the details need not concern us, but what does matter is that this experiment is equivalent to firing a beam of electrons at a barrier with two slits. When the experimenters allowed the electrons that passed through the slits to travel onward to a phosphor screen where their impact location was recorded by a tiny flash (the same kind of flashes responsible for the picture on your television screen), the results were astonishing. Thinking of the electrons as little pellets or bullets, you'd naturally expect their impact positions to line up with the two slits, as in Figure 4.3a. But that's not what Davisson and Germer found. Their experiment produced data schematically illustrated in Figure 4.3b: the electron impact positions filled out an interference pattern characteristic of waves. Davisson and Germer had found the smoking gun. *They had*



(a) (b)

Figure 4.3 (**a**) Classical physics predicts that electrons fired at a barrier with two slits will produce two bright stripes on a detector. (**b**) Quantum physics predicts, and experiments confirm, that electrons will produce an interference pattern, showing that they embody wavelike features.

shown that the beam of particulate electrons must, unexpectedly, be some kind of wave.

Now, you might not think this is particularly surprising. Water is made of H_2O molecules, and a water wave arises when many molecules move in a coordinated pattern. One group of H_2O molecules goes up in one location, while another group goes down in a nearby location. Perhaps the data illustrated in Figure 4.3 show that electrons, like H_2O molecules, sometimes move in concert, creating a wavelike pattern in their overall, macroscopic motion. While at first blush this might seem to be a reasonable suggestion, the actual story is far more unexpected.

We initially imagined that a flood of electrons was fired continuously from the electron gun in Figure 4.3. But we can tune the gun so that it fires fewer and fewer electrons every second; in fact, we can tune it all the way down so that it fires, say, only one electron every ten seconds. With enough patience, we can run this experiment over a long period of time and record the impact position of each individual electron that passes through the slits. Figures 4.4a–4.4c show the resulting cumulative data after an hour, half a day, and a full day. In the 1920s, images like these rocked the foundations of physics. *We see that even individual, particulate electrons, moving to the screen independently, separately, one by one, build up the interference pattern characteristic of waves.*

This is as if an *individual* H_2O molecule could still embody something akin to a water wave. But how in the world could that be? Wave motion seems to be a collective property that has no meaning when applied to separate, particulate ingredients. If every few minutes individual spectators in the bleachers get up and sit down separately, independently, they are *not* doing the wave. More than that, wave interference seems to require a wave from *here* to cross a wave from *there*. So how can

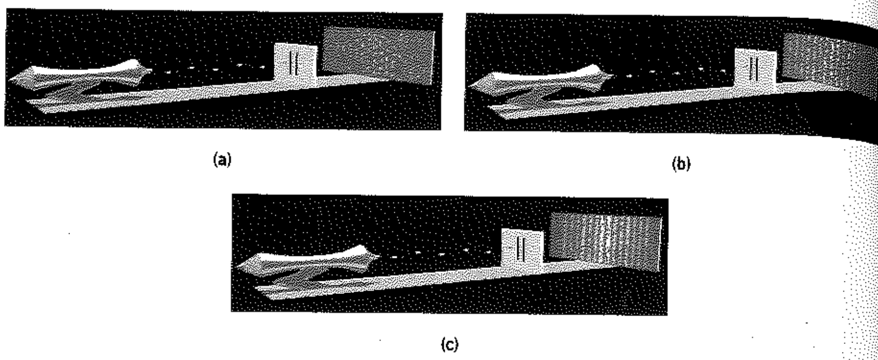


Figure 4.4 Electrons fired one by one toward slits build up an interference pattern dot by dot. In **(a)**–**(c)** we illustrate the pattern forming over time.

interference be at all relevant to single, individual, particulate ingredients? But somehow, as attested by the interference data in Figure 4.4, even though individual electrons are tiny particles of matter, each and every one also embodies a wavelike character.

Probability and the Laws of Physics

If an individual electron is also a wave, what is it that is waving? Erwin Schrödinger weighed in with the first guess: maybe the stuff of which electrons are made can be smeared out in space and it's this smeared electron essence that does the waving. An electron particle, from this point of view, would be a sharp spike in an electron mist. It was quickly realized, though, that this suggestion couldn't be correct because even a sharply spiked wave shape—such as a giant tidal wave—ultimately spreads out. And if the spiked electron wave were to spread we would expect to find part of a single electron's electric charge over here or part of its mass over there. But we never do. When we locate an electron, we always find all of its mass and all of its charge concentrated in one tiny, pointlike region. In 1927, Max Born put forward a different suggestion, one that turned out to be the decisive step that forced physics to enter a radically new realm. The wave, he claimed, is not a smeared-out electron, nor is it anything ever previously encountered in science. The wave, Born proposed, is a *probability* wave.

To understand what this means, picture a snapshot of a water wave that shows regions of high intensity (near the peaks and troughs) and regions of low intensity (near the flatter transition regions between peaks and troughs). The higher the intensity, the greater the potential the water wave has for exerting force on nearby ships or on coastline structures. The probability waves envisioned by Born also have regions of high and low intensity, but the meaning he ascribed to these wave shapes was unexpected: *the size of a wave at a given point in space is proportional to the probability that the electron is located at that point in space.* Places where the probability wave is large are locations where the electron is most likely to be found. Places where the probability wave is small are locations where the electron is unlikely to be found. And places where the probability wave is zero are locations where the electron will not be found.

Figure 4.5 gives a "snapshot" of a probability wave with the labels emphasizing Born's probabilistic interpretation. Unlike a photograph of water waves, though, this image could not actually have been made with a camera. No one has ever directly seen a probability wave, and conventional quantum mechanical reasoning says that no one ever will. Instead, we use mathematical equations (developed by Schrödinger, Niels Bohr, Werner Heisenberg, Paul Dirac, and others) to figure out what the probability wave should look like in a given situation. We then test such theoretical calculations by comparing them with experimental results in the following way. After calculating the purported probability wave for the electron in a given experimental setup, we carry out identical versions of

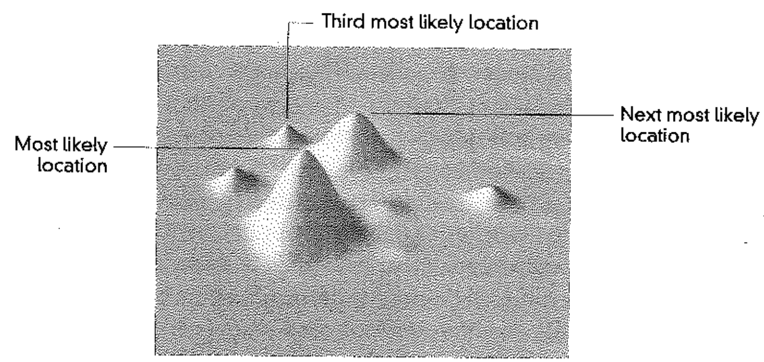


Figure 4.5 The probability wave of a particle, such as an electron, tells us the likelihood of finding the particle at one location or another.